

SPACECRAFT FIRE SAFETY AND MICROGRAVITY COMBUSTION RESEARCH

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1. Introduction

Fire safety is an important concern in our daily lives and it plays a special role in the human presence in space. In a spacecraft, the outside environment is hostile and the opportunity to escape is small. Rescue mission is difficult and time consuming. As a result, we should avoid the occurrence of fires in spacecraft as much as possible. If a fire occurs, we need to keep it small and under control. This implies that the materials used on board the spacecraft should be screened carefully, all the machines and devices need to be operated without accident, fire detectors have to function properly. Once a fire is detected, it can be extinguished quickly and the cabin can be cleaned up to restore operation and sustain life.

2. Special Features in Spacecraft Environment

Although we may agree with the above strategy in dealing with potential fires in spacecraft, there are a number of technical issues that hinder its implementation. These are related to the special spacecraft environment which include:

- (a) Microgravity. Gravity influences fire in a fundamental manner. Our previous knowledge on fire and fire fighting are all from the experience on earth. Some of these may not be readily applicable to the microgravity environment in the spacecraft.
- (b) Flow condition. Although the buoyant-induced flow from flame is negligible, ventilated flows exist in manned spacecraft. These are purely forced flow with velocities varying from a fraction of one cm/s to several tens of cm/s depending on the locations. The flow velocities, especially in the lower portion of this range, are below the buoyant induced velocity around flames in normal gravity. The flame behavior in these low-speed forced flows can be quite different from what we know from the buoyant terrestrial fires.
- (c) Atmosphere. The nominal atmosphere in the International Space Station Alpha and the U.S. Space shuttles is standard air (21% O₂ and balanced with N₂ at one atmospheric pressure). However, this manufactured 'air' can have a fluctuated oxygen percentage. For example, in the Russian space station Mir, the reported O₂

percentage has been as high as 25%. Combustion behavior is highly sensitive to the oxygen percentage. In addition, to prepare for the space walk, astronauts will be exposed to 30% O₂ for a period of time.

3. Microgravity Combustion Research relevant to Spacecraft Fire Safety

One of the major uncertainty in implementing the spacecraft fire safety strategy is the lack of a more complete understanding of the flame behavior in the absence of gravity. In particular, how is the combustion behavior in microgravity different from that in normal gravity? A few selected examples are given below to illustrate the differences.

- (a) The existence of low-speed flammability limit. It is well known that diffusion flames cannot be sustained in an air stream when the air velocity is too large. This high-speed blowoff limit is the result of insufficient residence time in the flame stabilization zone. When the air velocity becomes too small, e.g. of the order of a couple of centimeters per second, the flame may also go out [1]. This low-speed extinction limit is due to too large a radiative heat loss compared with the combustion heat release, a consequence of decreased convective flow [2-5]. At an intermediate flow velocity, the solid material is the most flammable (i.e. has the lowest limiting oxygen index or needs the greatest amount of suppressant to extinguish). This most flammable flow velocity is estimated to be around 5-10 cm/s. This is within the air ventilation flow regime in the spacecraft but lower than the buoyant-induced flow in a flame in normal gravity. Therefore, a material that is not flammable in a normal gravity test can be flammable in a spacecraft. This has a profound implication to material screening which, for all practical purpose, has to be carried out in a terrestrial environment.
- (b) The existence of the low-speed extinction limit, however, suggests that if a fire is detected, the ventilation flow should be turned off. This is indeed the present proposed procedure in the spacecraft operation. Note that by turning off the flow the spread of smoke will also slow down.
- (c) The amplification of the influence of flame radiation in microgravity produces a number of trend reversal phenomena between normal- and micro-gravity [6,7]. These include: the ranking of material flammability index [8], the relative effectiveness of the fire suppressants [9,10], the reversal of flame spread rates [9,11] and the crossover between concurrent and opposed flow spreads [12,13]. These trend reversals prevent a straightforward extrapolation of the normal gravity data to spacecraft environment. A better scientific understanding of these phenomena is needed for an intelligent application of the material screening process, for the selection and the application of the suppressants and for the design of fire fighting procedures.
- (d) The lack of buoyancy also affects the material ignition characteristics. Before a gas-phase ignition to occur, a combustible mixture has to form. Instead of being dispersed by buoyant convection, the hot pyrolyzed fuel vapor tends to stay close to point of heating in microgravity. This accelerates the formation of a combustible mixture and a quicker ignition [9]. If the external heating of the solid is by a radiation source, the ignition delay will also be shortened since there is less convective cooling in the microgravity [14].

(e) Smoldering in microgravity has the potential to be more serious than in normal gravity. Smoldering is promoted by more oxygen supply and less heat loss. Low speed flow in microgravity slows down the oxygen transport but also decreases the convective heat loss [15]. More research is needed to seek out the net effect of these competing influences.

(f) Because of the different travel history of a particle, the soot formed in a microgravity flame has different size and structure [16]. This may affect the sensitivity of the fire detector. Furthermore, flame in microgravity under certain conditions will not produce soot. Its effect on the fire detection needs to be evaluated. A related problem is the placement of the detectors and how many are needed. The smoke and hot combustion products will go downstream with the forced ventilation flow in the spacecraft, not to the ceiling as in normal gravity. Can we miss detecting a secondary fire if the ventilation is turned off?

With the International Space Station already in orbit and an expected busy activity for the next 15 (at least) years, we are looking for more opportunities to perform longer-duration microgravity experiments. Some of these will have direct bearings on fire safety issues in the ISS and spacecraft beyond the earth orbit [17]. From a scientist's point of view, this type of research is both exciting and rewarding. It is exciting because we are exploring the unknowns-in combustion regimes that have little data and the results are very often unexpected. It is rewarding because our effort may make it safer for the human exploration in space.

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